

## South American Summer Monsoon of 1997/98 and 1998/99

William K.-M. Lau and Jiayu Zhou\*

Code 913, Laboratory for Atmospheres  
NASA/Goddard Space Flight Center  
Greenbelt, MD 20771

### Introduction

It is well known that during El Niño years, severe drought occurs in the area of Amazon and northeastern Brazil. According to the linear model result (Silva Dias *et al.* 1983) the reduced latent heating over the Amazon may lead to a weaker than normal upper tropospheric Bolivian high. As a result, some studies have suggested a weaker South American summer monsoon (SASM) during El Niño years (Bell *et al.* 1999).

Using reanalysis data, Zhou and Lau (1999) found a statistically significant positive correlation between the tropical eastern Pacific sea surface temperature (SST) and the strength of low-level jet (LLJ) along the eastern foothills of the tropical-subtropical Andes. Douglas (1999) also showed a strong LLJ at Santa Cruz, Bolivia during a special pilot balloon observation period in 1997/98 El Niño austral summer. Since this LLJ is an integral part of the monsoon system (Zhou and Lau 1998) in the summertime, these results indicated that SASM could be stronger than normal in El Niño years.

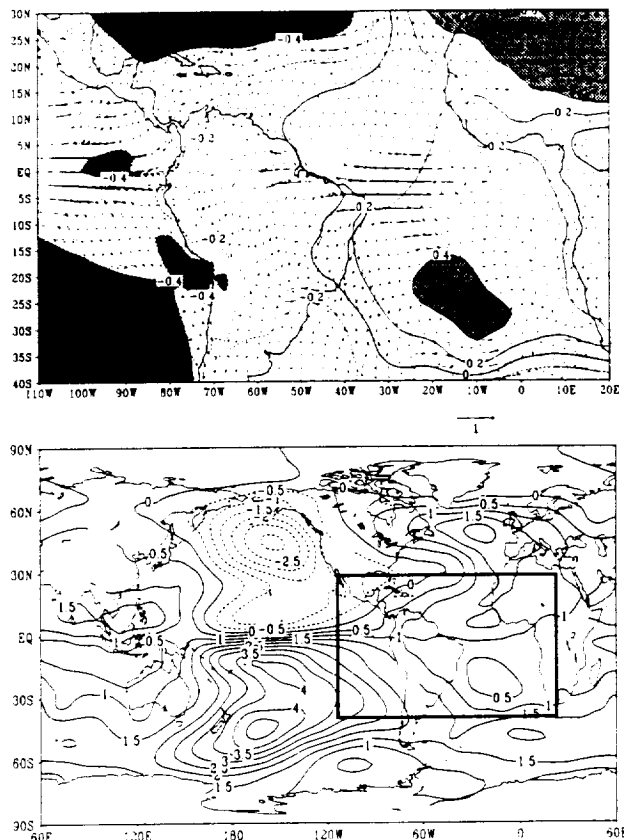
To clarify this issue, we conducted an investigation on SASM anomaly in the recent ENSO event of 1997/98 El Niño and 1998/99 La Niña. In the following, we first give a brief review on SASM and the interannual variability of summer rainfall over South America. Then, the impact of 1997-99 ENSO on the South American regional thermal structure and its dynamical consequences to SASM will be discussed.

### Data

The data used in this study are the National Center for Environmental Prediction (NCEP) reanalysis, the NCEP SST and the monthly mean CPC (Climate Prediction Center) Merged Analysis of Precipitation (CMAP).

### SASM and interannual variability of summer rainfall

From austral spring to summer, sea level pressure increases over northwest Africa and decreases over



**Fig. 1** Regression of the DJF CMAP rainfall principal component of the ENSO mode with GEOS-1 SLP and 850-hPa wind (upper) and that with 850-hPa streamfunction (lower). (From Zhou and Lau 1999)

Gran Chaco of South America, as a result of rapid heating over the South American land mass following the seasonal migration of the sun. The low level flow, which is an integral component of the South American summer monsoon migrates from the northwestern African continent, flows along the northern equatorial Atlantic Ocean, crosses the equator over the east of the tropical Andes and brings the rainy season to the

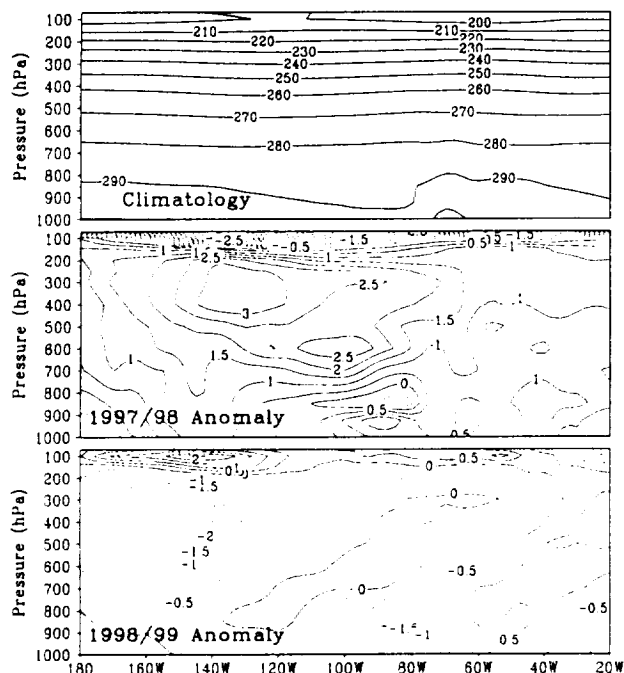
Corresponding author address: Dr William K.-M. Lau, Code 913, NASA/GSFC, Greenbelt, MD20771.

E-mail: [lau@climate.gsfc.nasa.gov](mailto:lau@climate.gsfc.nasa.gov)

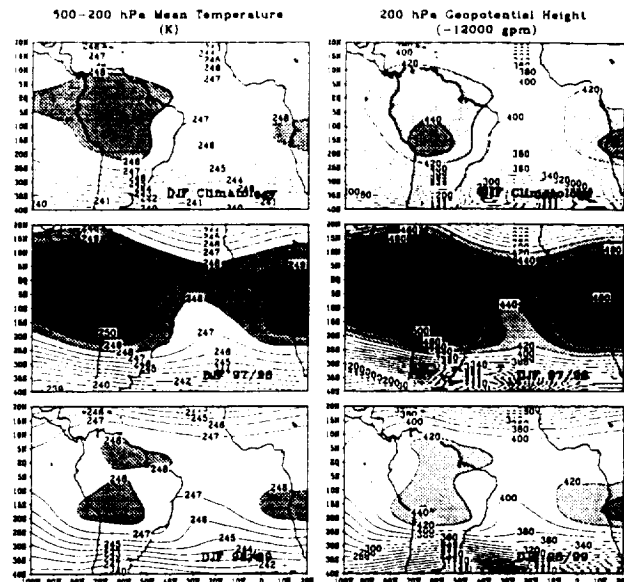
\* SM&A Corporation

subtropical South America. In November, the forefront of heavy precipitation advances southward more than 10 degrees, which signifies the SASM onset. During DJF (December, January and February) SASM prevails over most tropical-subtropical land area. The maximum rainfall axis tilts northwest-southeastward, coinciding with the South Atlantic convergence zone (SACZ), which is most active of this time of the year. The SASM rainfall regime can be clearly identified according to the seasonal rainfall concentration, which shows that the subtropical South American continent (25°-10°S) receives almost 50% of the local annual rainfall from SASM precipitation in DJF. This rainfall regime is distinct from that over northern Northeast Brazil and the equatorial Atlantic, where large concentration of annual rainfall is in austral fall.

The ENSO impact on the South American summer rainfall has been explored extensively by many previous studies, which showed during El Niño years severe drought occurred in the area from Northeast Brazil to central Amazon and flood over Uruguay-southern Brazil and the west coast of Ecuador. Figure 1 (from Zhou and Lau 1999) shows the dynamical response of the ENSO anomaly in the lower troposphere. It reveals that during El Niño years the northwest African high is enhanced, and the subtropical highs of the South Pacific and the western North Atlantic are weakened. These anomalies



**Fig. 2** Vertical cross-section of DJF temperature along 15°S. From top to bottom shows the climatology, the 1997/98 anomaly and the 1998/99 anomaly, respectively.



**Fig. 3** DJF 200-500 hPa mean temperature (left) and 200 hPa geopotential height (right) of climatology (upper), 1997/98 (middle) and 1998/99 (lower).

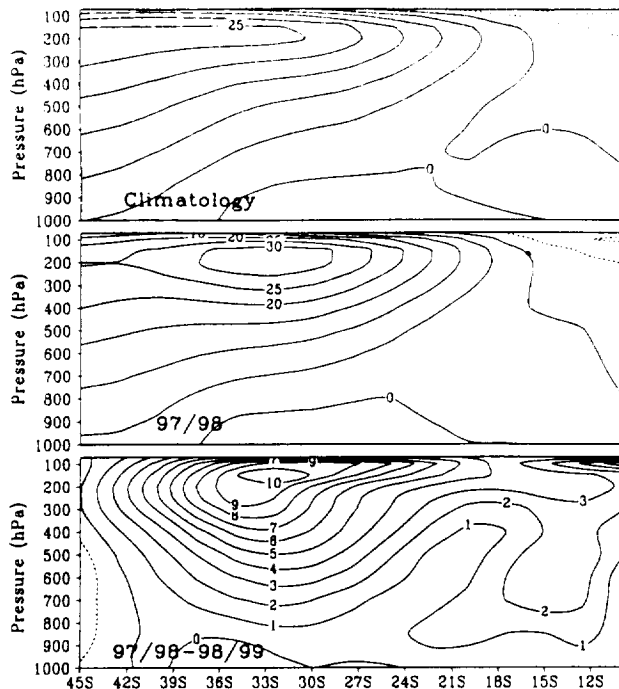
are the integral parts of the global ENSO response. Consequently, the flow around the outskirts of the tropical South Atlantic high and the summer monsoon flow over the equatorial Atlantic and along the eastern foothill of the Andes are substantially enhanced. These two branches of anomalous wind diverge over northeastern Brazil and converge over southern Brazil. Over the west coast of Ecuador, anomalous convergence is encountered due to above normal westerlies from the displaced Walker circulation over the eastern equatorial Pacific and the increased easterlies of enhanced summer monsoon circulation along equatorial Amazon Basin. These changes imply abnormal low-level moisture convergence, which is consistent with the aforementioned anomalous rainfall distribution over South America.

#### SASM anomalies in 1997/98 and 1998/99

The years 1997-1999 witnessed the strongest El Niño event of the century. During this time period, the typical ENSO-related rainfall anomaly pattern was reported by a number of studies (Bell *et al.* 1999). The following analysis will focus on the SASM system and the cause of the anomaly.

##### a. Temperature anomaly and hydrostatic response

As a deep convective system, summer monsoon is thermally driven and vertically extended from the surface to the upper troposphere. To search for the ENSO impact on the monsoon system, a vertical cross-



**Fig.4** DJF zonal wind zonally averaged from 80°W to 50°W. From top to bottom shows the climatology, the 1997/98 anomaly and the difference between 1997/98 and 1998/1999, respectively.

section of the temperature along 15°S is plotted (Fig. 2). It shows that in DJF 1997/98 the El Niño induced tropospheric warming starts from 1°K at the surface of the Niño 3 region and enhances upward to a maximum of 3°K between 500 and 150 hPa. In the upper troposphere the warming area expands eastward, reaching South America at about 1.5°K. In DJF 1998/99, the anomaly sign is completely reversed and the intensity weaker than that in DJF 1997/98, especially over South America.

Figure 3 shows the geographical distribution of 500-200 hPa mean temperature and 200 hPa geopotential height. It is evident that during DJF 1997/98 (1998/99) of El Niño (La Niña) Bolivian high is much stronger (weaker) than that shown in the climatology as a result of hydrostatic response to the tropospheric warming (cooling). This result indicates the primary importance of the thermal impact on the intensity of Bolivian high during 1997-99 ENSO episode. The dynamical forcing (Rossby wave propagation induced by Amazonian transient convective heating) suggested by previous studies is secondary in this case.

#### *b. Dynamical impact and anomalous circulation*

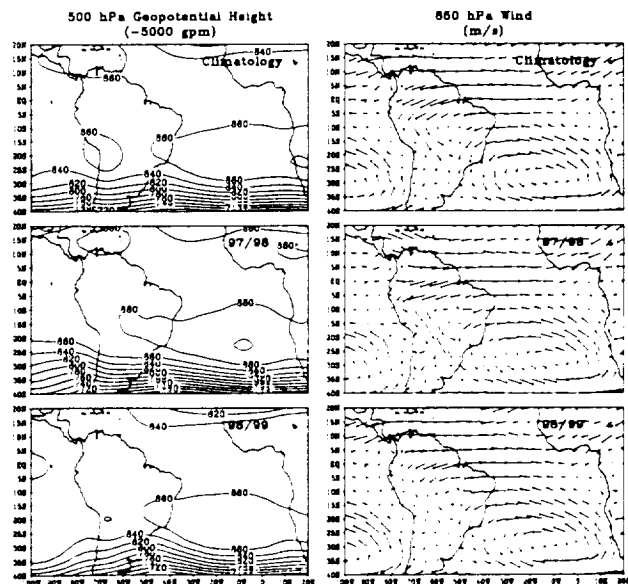
In strong El Niño years, because of the tropospheric warming in the tropics, the meridional

temperature gradient increases in the subtropics, which has great impact on the strength of the subtropical westerlies in the upper troposphere. Figure 4 shows the vertical cross-section of zonal mean subtropical westerlies along a north-south strip over South America. In DJF 1997/98 a jet core of greater than 30 m/s is located near 33°S at 200 hPa, where the westerlies are almost 10 m/s (5 m/s) stronger than that in DJF 1998/99 (climatology). At the north of the jet, anomalous zonal wind shear produces significant positive vorticity anomaly, which is dynamically consistent with the enhancement of Bolivian high.

During 1997-98, the SASM flow pattern is in agreement with that based on previous ENSOs. Figure 5 demonstrates a sharp contrast of LLJ along the eastern side of subtropical Andes and that of the South Atlantic subtropical high between 1997/98 and 1998/99 austral summer. A systematic strengthening (weakening) of the monsoon system introduced by El Niño (La Niña) is evident.

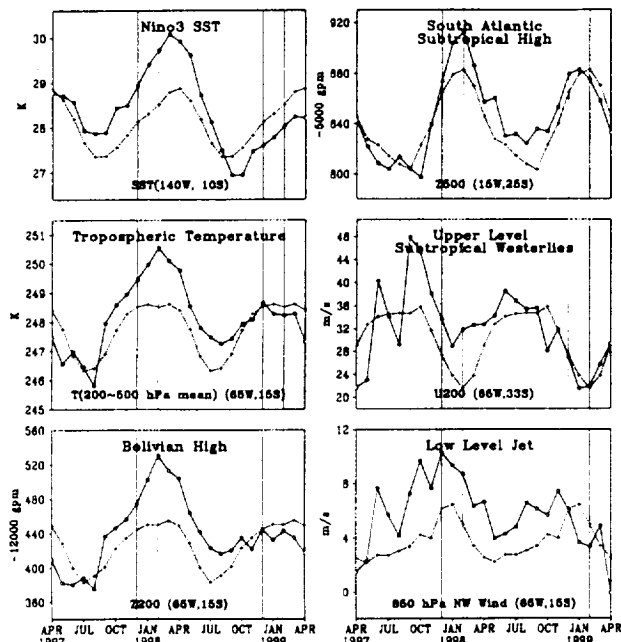
#### *c. Changes in annual cycle and characteristics of SASM development*

Since the monsoon evolution is part of the regional annual cycle, it is important to know how the annual cycle is affected by ENSO. Figure 6 shows the time evolution of each key component and compares that with the annual cycle. From the figure we can see the annual cycles of all components are amplified during 1997/98 El Niño and slight weaker during 1998/99 La Niña. The warming of SST over Niño 3 region started



**Fig. 5** DJF 500 hPa geopotential height (left) and 850 hPa wind (right) of climatology (upper), 1997/98 (middle) and 1998/99 (lower).

from June 1997 and ended in August 1998. A two months delay can be found in the progressions of tropospheric mean temperature and upper tropospheric geopotential high anomalies over Altiplano plateau, and even longer time delay in the evolution of the South Atlantic subtropical high anomaly. The upper troposphere subtropical westerly anomaly seems to be more sensitive to the change of SST and, evolves approximately in phase with the Niño 3 SST anomaly. The initiation of the positive anomaly of the low-level northwesterlies along the eastern foothills of subtropical Andes accompanies the enhancement of the upper tropospheric subtropical westerly anomaly, while the termination seems to be more related to the reduction of the local geopotential height anomaly, about one month later (earlier) than that of Bolivian high (South Atlantic subtropical high) anomaly.



**Fig. 6** Time evolution of key components, named at the top and specified at the bottom of each figure. The lines marked by the cross sign indicate the annual cycle.

Further examination of the SASM development shows that the convective heating over subtropical Andes is more intense and congregated in the period from mid-summer to early spring in 1997/98 El Niño year. In contrast, during 1998/99 La Niña episode the summertime convective activities are weak and spread over a longer time period, in which major breaks can be identified. In relation to the heating anomaly, a single jet in 1997/98 and a double jet in 1998/99 characterize the upper-level subtropical westerly.

## Conclusions

In this paper we have conducted an investigation to compare and contrast the variations of the SASM system in recent two SST extreme years of 1997/98 (El Niño) and 1998/99 (La Niña). Using the National Center for Environmental Prediction (NCEP) reanalysis, our result shows a substantial increase of the mid-tropospheric temperature above the Altiplano Plateau in austral summer of 1997/98. Accompanied with that, the Bolivian high is much stronger than normal during DJF 1997/98. The South Atlantic subtropical high is enhanced and expands westward into eastern Brazil. As a result, a strong single upper-tropospheric jet over the subtropical continent and an intense NW LLJ along the eastern foothill of the tropical-subtropical Andes are generated. These features characterize a strong SASM. The situation is completely reversed in 1998/99, suggesting a weakening of the SASM. The annual cycle was amplified in 1997/98 and reduced in 1998/99. In addition, this study demonstrates the primary role of the thermal forcing in strengthening of Bolivian high during 1997/98 El Niño episode, which more than compensates the possible dynamical impact due to reduced heating over Amazon.

**Acknowledgments.** We thank Drs. Pingping Xie and Phillip A. Arkin for providing us the monthly mean CMAP data used in this study. This research is supported by the Earth Observing System / Interdisciplinary Science investigation on hydrological processes and climate, and the Global Modeling and Analysis Program of NASA, Mission to Planet Earth Office.

## References

- Bell, G.D., M.S. Halpert, C.F. Ropelewski, V.E. Kousky, A.V. Douglas, R.C. Schnell, and M.E. Gelman, 1999: Climate Assessment for 1998. *Bull. Amer. Meteor. Soc.*, **80**, S1-S48.
- Douglas, M., 1999: The low-level jet at Santa Cruz, Bolivia during January-March 1998 pilot balloon observations and model comparisons. *10<sup>th</sup> Symposium on Global Change Studies*, 10-15 January 1999, Dallas, Texas. 223-226.
- Silva Dias, P.L., W.H. Schubert, and M. DeMaria, 1983: Large-scale response of the tropical atmosphere to transient convection. *J. Atmos. Sci.*, **40**, 2689-2707.
- Zhou, J. and K.-M. Lau, 1998: Does a monsoon climate exist over South America? *J. Climate*, **11**, 1020-1040.
- , and —, 1999: Interannual and decadal variability of summer rainfall over South America. *10<sup>th</sup> Symposium on Global Change Studies*, 10-15 January 1999, Dallas, Texas. 516-519.